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**FREQUENCY REUSE
THROUGH RF POWER MANAGEMENT
IN SHIP-TO-SHIP DATA NETWORKS**

by

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A computer simulation was developed to determine the bit error rate (BER) of a QPSK system in a Ricean fading channel with one cochannel interferer. The simulation generates plots of energy per bit to one-sided noise power spectral density ratio (E_b/N_0) versus BER. Simulation results are used to compute the minimum range (R) at which the channel can be reused while maintaining an average BER of 10^{-6}. The results show that even when no power control is used the channel can be reused at a range, R, of approximately 45 kilometers. This range can be reduced to less than 20 kilometers if an interfering ship can reduce its output power by 30 dB.

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FREQUENCY REUSE THROUGH RF POWER MANAGEMENT IN SHIP-TO-SHIP DATA NETWORKS

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ABSTRACT

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LIST OF ACRONYMS

AGC	Automatic Gain Control
ARG	Amphibious Readiness Group
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BG	Battle Group
bps	bits-per-second
DA	Design Architect
Hz	Hertz
LOS	Line-of-Sight
MFSK	M-ary Frequency Shift Keying
MG	Mentor Graphics
MPSK	M-ary Phase Shift Keying
MQAM	M-ary Quadrature Amplitude Modulation
NCCOSC	Naval Command, Control, and Ocean Surveillance Center
NRaD	Naval Command, Control, and Ocean Surveillance Center, RDT&E Division
PDF	Probability Density Function
QAM	Quadrature Amplitude Modulation
QOS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RDT&E	Research, Development, Test, and Evaluation
RF	Radio Frequency
RSL	Received Signal Level
RV	Random Variable
SATCOM	Satellite Communications
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
TX	Transmission

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I. INTRODUCTION

The Naval Command, Control and Ocean Surveillance Center(NCCOSC), RDT&E Division (NRaD) is conducting applied research towards the development of a high-data-rate (HDR), line-of-sight (LOS), digital communication system for ship-to-ship, ship-to-shore, and ship-to-relay connectivity[1]. The objective of the research is to create a high-capacity wireless communications network within a Battle Group (BG) or Amphibious Readiness Group (ARG), thereby allowing the flow of voice, video, and data between platforms and connecting the communications assets from each of the different platforms. This network will allow, for instance, a surface combatant without HDR satellite communications (SATCOM) assets access to shore sites if such capability existed on another ship, e.g., an aircraft carrier. In addition, the robustness of the entire BG or ARG communications infra-structure is improved by being able to share the communication assets of all.

NRaD is proposing a wireless network capable of transmitting full-duplex data at 1536 kilo-bits-per-second (kbps) operating in the 225MHz-400MHz frequency band. Such a network will occupy 24 channels, each 25-KHz wide, for a total 600 kHz bandwidth. Emphasis of the development effort is on the reliability of the communications link at useful

ranges between mobile platforms such as Navy ships, helicopters, and sub-sonic fixed-wing aircraft and various shore sites.

Because of the limited bandwidth available (600 kHz) and the desire to maximize the data throughput(>1536 kbps), bandwidth-efficient data modulation schemes such as M-ary quadrature amplitude modulation (MQAM) and M-ary phase shift keying (MPSK) must be employed.

In addition to the bandwidth requirement, it is desired to increase the number of simultaneous links within the same 600 kHz channel. There are various techniques that can be used to accomplish this task, such as increasing the number of bits transmitted per data symbol, i.e., use of 8QAM, 8PSK, 16QAM, etc. Another technique that can be used to allow multiple simultaneous links is the use of radiated Radio Frequency (RF) power control. The use of radiated RF power control in order to optimize the use of available bandwidth is the subject of this thesis.

A typical maritime scenario without the use RF power control could include exchange of data within a BG as depicted in Figure 1.1. Ships A and B exchange data using a 600 kHz channel (channel 1), ships C and D exchange data using channel 2, for a total 1200 kHz bandwidth. It is of interest to study the merits of limiting the radiated power so that a particular channel can be re-used by other units. For example, for the given topology in Figure 1.1, all units

could share channel 1. This can be accomplished by reducing the transmitted power to the minimum necessary to maintain a desired quality of service (QOS). This power control scheme will create moving cells similar to those in a cellular phone network. This channel re-use, however, introduces the problem of cochannel interference, which can be significant if the cells begin to overlap.

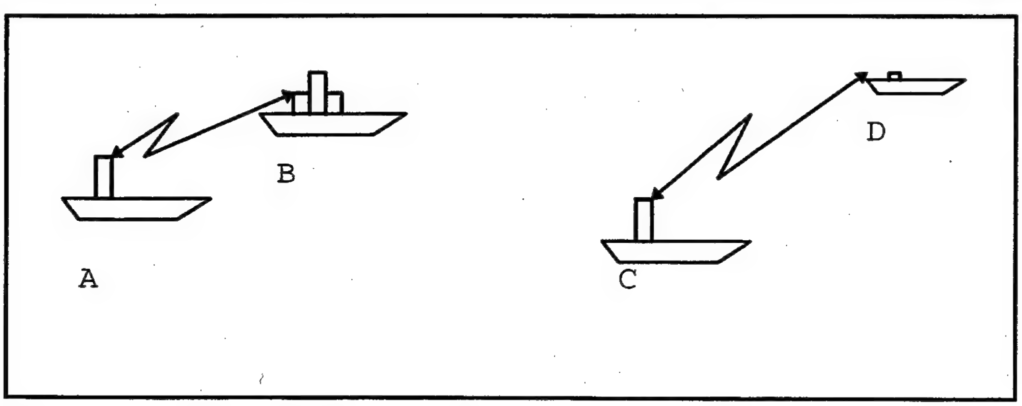

Figure 1.1 RF Wireless Communications Network Within a BG or ARG

The goal of this thesis is to study the characteristics and effect of this cochannel interference for QPSK modulation and to determine the merits of using radiated power control as a mean to achieve frequency reuse. A computer simulation using the Mentor Graphics (MG) software communication tools was developed to simulate and study the behavior of a QPSK communication system with cochannel interference. From the MG simulation we can estimate the link availability of a system subjected to power control and frequency reuse.

The remainder of this thesis is organized as follows. Chapter II discusses the link budget analysis and the effect of power control for a simplified ship-to-ship, LOS data link. Chapter III covers theoretical aspects of determining the probability of bit error for a fading channel with cochannel interference. Chapter IV describes the MG environment, the simulation developed, and the various test cases employed. Chapter V presents the results obtained from the simulation. Conclusions are presented in Chapter VI.

II. LINK ANALYSIS FOR SHIP-TO-SHIP DATA COMMUNICATIONS

A. SYSTEM DESCRIPTION

A simplified block diagram of a full duplex shipboard LOS data communications system is shown in Figure 2.1. The transmission (TX) line and antenna coupler losses used are representative values and were reported in [2].

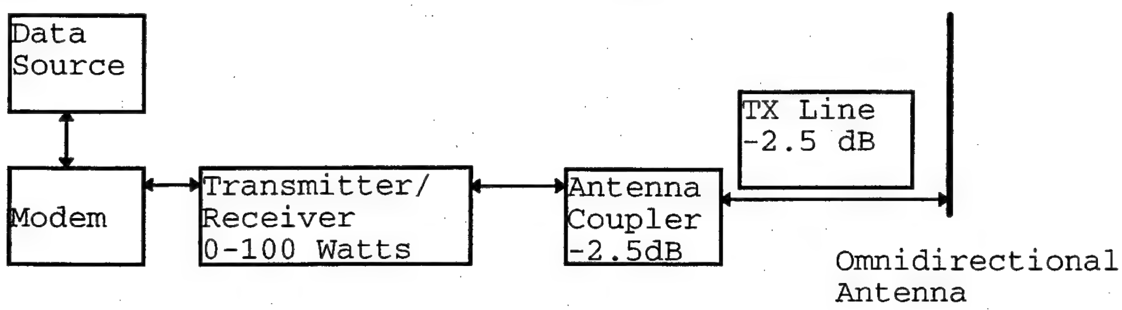

Figure 2.1 Shipboard LOS Data Communications System

B. LINK ANALYSIS

The median received signal level (RSL) is determined from the total transmitted power, free-space propagation losses, diffraction by the earth, antenna height, cable losses, and antenna losses or gains. Free-space propagation losses, in dB, are given by

$$L_{fs} = 10 \times \log_{10}\left(\frac{4\pi d}{\lambda}\right)^2$$

where d is the distance from the source and λ is the carrier signal wavelength.

Figures 2.2 and 2.3 are plots of the median propagation losses at 231.5 MHz and 400 MHz, respectively, for ship-to-ship LOS communications assuming an antenna height of 25 meters on each platform[3]. The difference between free-space and ship-to-ship attenuation is due to diffraction by the earth's surface and is inversely proportional to the height of the antennas. The higher the antennas, the closer the losses will be to free space losses. The RSL will fluctuate randomly about this median level. The reliability of the link will be a function of the magnitude and the rate of these fluctuations(fade rate).

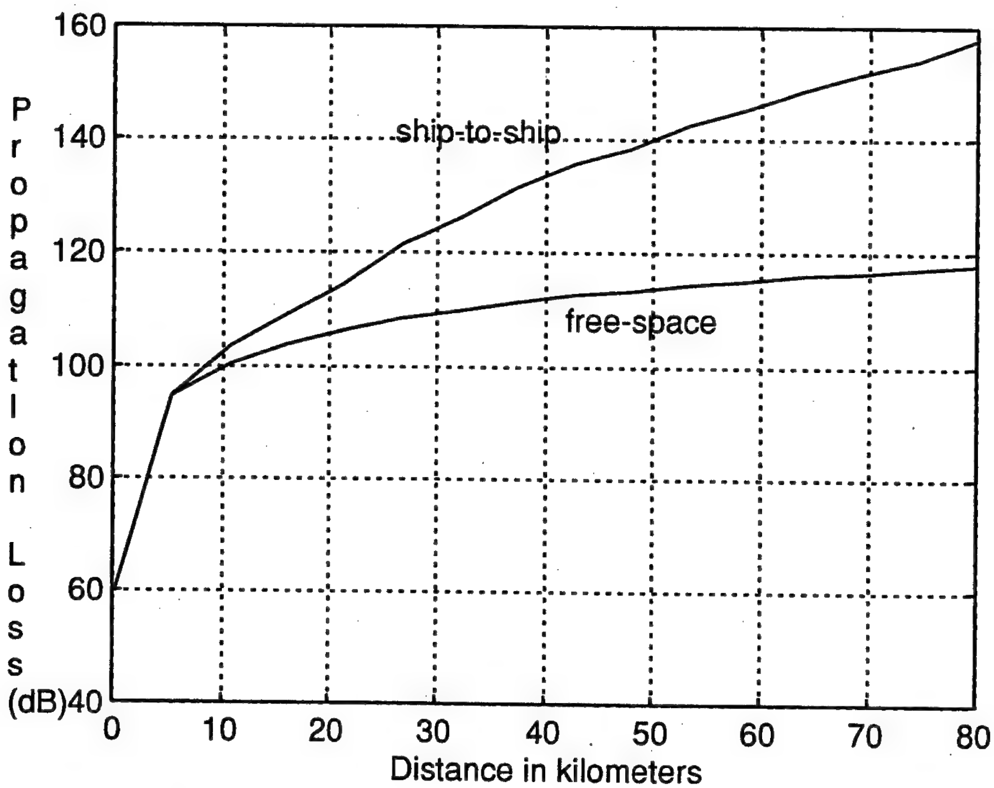

Figure 2.2 Median total propagation loss and free-space loss for 231.5 MHz [3].

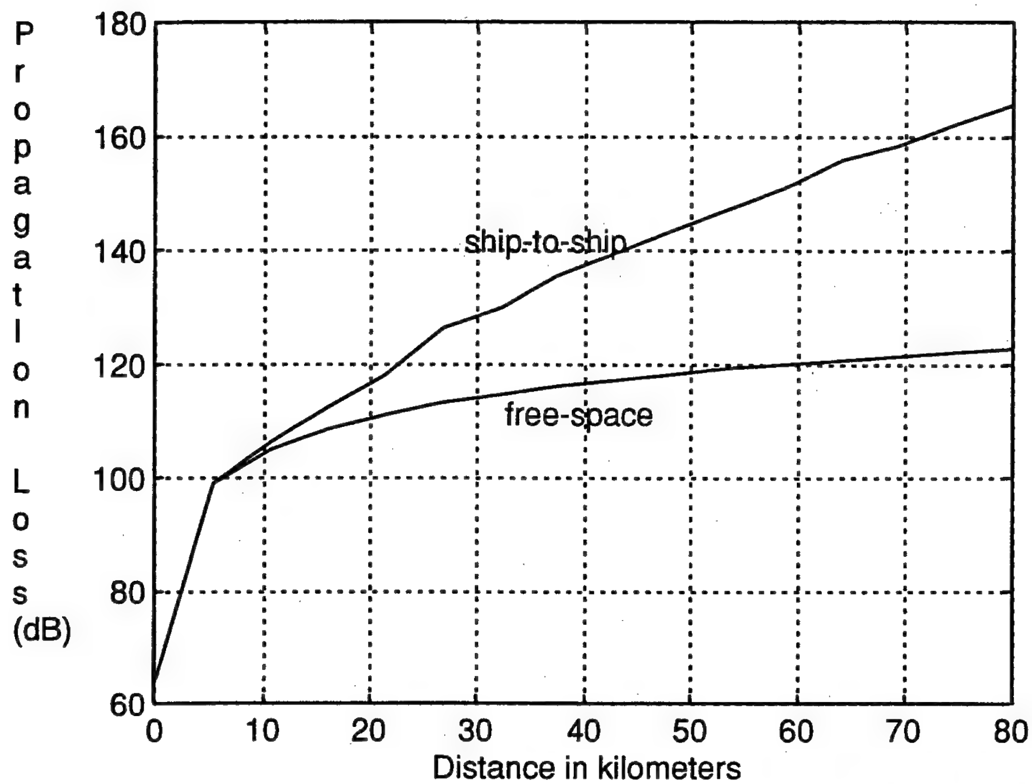

Figure 2.3 Median total propagation loss and free-space loss for 400 MHz [3].

The reliability is defined as

$$reliability(\%) = 100(\%) - outage(\%)$$

where the outage is expressed as the percentage of seconds in which the bit error rate (BER) is greater than 10^{-6}. The RSL is affected by many other factors, such as ship and antenna movement and atmospheric conditions such as [3]:

a. Enhanced(or reduced) RSL due to evaporation ducts close to the water surface. The RSL will be

enhanced if the receive antenna is within the duct and will be reduced if the receive antenna is outside the duct.

b. Multipath interference due to refraction of the transmitted signal off the troposphere. Refraction by the atmosphere tends to create a frequency non-selective (flat), rapid fading which becomes worse as the path distance increases.

c. Multipath interference due to reflection of the transmitted signal off the surface of the water. Reflection tends to create frequency-selective, slow fading which can be a function of sea state.

d. Diffraction, or shadowing, effects caused by the earth's surface will decrease the RSL.

The primary means for maintaining a reliable communication link when fading is flat and a single omni-directional antenna is used is to increase the fade margin. Increasing the fade margin, however, increases the amount of interference power at other sites reusing the channel. A compromise must be reached between the amount of fade margin and link availability. Increasing the fade margin, i.e., higher transmitted power, improves link availability in the current "cell" while at the same time degrading link availability at cells reusing the channel. This point can best be quantified by determining the minimum transmitted

power needed to establish a BER of 10^{-6} at a given range. We can then determine the interference power at remote cells reusing the channel.

In order to estimate reliable communication ranges it is necessary to conduct link budget calculations. A data rate of 1.544 Mbps (T1 link) is assumed. Propagation losses are determined from Figure 2.1. From Figure 2.2 we can see that the transmitted signal will experience a total of 10 dB loss, 5 dB on each end, from the antenna coupler and cables. In order to simplify calculations it will be assumed that only 10 dB watts (20 dB watts - 10 dB loss) or 40 dB milliwatts (dBm) are available for transmission. Antenna gain is assumed to be zero dB.

At the receiver end the RSL can be expressed as $RSL = P_t - L_{prop}$. Without loss of generality, it is assumed that a mean RSL of -80 dBm is required to establish a bit energy (E_b) to noise power spectral density (N_o)ratio (E_b/N_o) of 10.6 dB (BER = 10^{-6}), where $E_b = RSL/(data\,rate)$. The transmitted signal can sustain a total loss of 120 dB (40dBm - (-80dBm)) and still maintain the desired BER. From Figure 2.3 we can see that a range of approximately 22 km will result in a loss of 120 dB. In other words, if we assume no fading, this is the maximum range at which we can achieve the target BER(10^{-6}). If we desire a fade margin of

15 dB, the transmitter must provide the additional power for a total of 55 dBm. If the transmitter is limited to 40 dBm, the fade margin can only be achieved by reducing the communications range. From Figure 2.3 we can see the maximum range is now around 8-10 km.

Suppose for example that a remote cell reusing the channel can tolerate a Carrier/Interference ratio of 25 dB and still maintain a BER of 10^{-6}. Since we require an RSL of -80 dBm, the interfering signal cannot be greater than -105 dBm. Therefore, the interfering signal must suffer a total loss of 145 dB or higher. From Figure 2.3 we see that this corresponds to a mean distance of 55 km between the interferer and the cell reusing the channel. However, if the interferer increases his output power to 55 dBm, to compensate for fading, the distance between the interferer and the receiver must be increased to more than 80 km.

From this simple scenario it is evident that we must transmit excess power to allow for fading. However, in order to reduce cochannel interference the transmitted power must be minimized. These two contradicting requirements can be optimized by a power control scheme. An effective power control scheme transmits only the amount of power necessary to maintain the required BER. During signal fades the receiver will feed back information to the transmitter indicating that additional power must be transmitted. This

feedback path can be implemented as an in-band or out-of-band channel. Our only concern here is that the feedback be provided at a rate higher than the fade rate. For a ship-to-ship LOS data network this rate is estimated to be in the order of hundreds of hertz. Even when power control is in place, a fade margin must be established. However, this fade margin can be reduced significantly by efficient power control. We can define a measure of the power control algorithm's effectiveness as:

$$effectiveness = \frac{fade\ \ margin\ \ without\ power\ control - fade\ margin\ with\ power\ control}{fade\ margin\ \ without\ power\ control}$$

where fade margin here refers to that fade margin required to maintain a specified link availability. From the previous example, we deduce that a 100% efficient power control scheme allows frequency overlapping cells within a range of approximately 55 km. Without power control, 0% effectiveness, this range must be extended to approximately 80 km.

It must be emphasized that the ranges mentioned here apply to a representative system, i.e., specific antenna (omnidirectional) height, specific power output, and specific receiver sensitivity. The effect of power control, however, is independent of the system being employed. Its main effect is to reduce the ranges at which the frequency band can be reused. Before a power control scheme is

implemented, a tradeoff analysis must be conducted to determine if the reduction in frequency reuse ranges outweighs the cost and complexity associated with power control implementation.

The next chapter discusses the performance of a QPSK system in a fading channel with cochannel interference. These effects must be considered if an accurate description of the effects of frequency reuse is to be developed.

III. THEORETICAL DERIVATION OF PROBABILITY OF BIT ERROR WITH COCHANNEL INTERFERENCE AND FADING

The radio propagation environment places fundamental limitations on the performance of wireless communication systems. Data transmissions are subjected to two major sources of degradation, fading and cochannel interference. Fading results from multipath propagation and cochannel interference is due to reuse of radio frequencies. Before considering the subject of radiated power control these effects must be considered. Various models have been used to analyze the effects of fading and cochannel interference on mobile channels. For this thesis work, cochannel interference will be modeled using what has been described as the precise model[4]. This model assumes that cochannel interference is being generated by other sources sharing the same channel and using the same data modulation technique, e.g., QPSK, at the same data rate. This is justified on the basis that interference will most likely be generated by other ships using similar data modems but at different geographical locations. For the maritime environment being considered it is assumed that cochannel interferers experience Rayleigh fading, while the desired signal will experience Ricean fading.

A. PROPAGATION CHANNELS

The channel models to be assumed in this thesis are as follows. For a thorough description of these and other channel models see [5].

1. Nonfading Channel

This is the simplest type of channel modeled in a communications system. The noise is assumed to have a constant power spectral density over the channel bandwidth and its magnitude is modeled as a zero-mean random process with a Gaussian probability density function (PDF). In practice this channel occurs when there is no multipath propagation. The Gaussian channel is also important for providing an upper bound on system performance. Throughout this thesis bit error rates will be compared to those obtained for a nonfading channel.

2. Rayleigh Channel

If each multipath component in the received signal is independent then its envelope can be modeled as a Rayleigh PDF. For this type of channel, since the received signal is the sum of multiple components of similar amplitude but different phases, the individual components may add constructively or destructively. Destructive interference will result in fading of the signal and consequently a marked increase of the BER.

3. Ricean Channel

If a dominant path, such as LOS, exists in addition to the many scattered paths, the depth of the fades may be significantly reduced. For this case the envelope of the received signal can be modeled as a Ricean distribution. Defining K=(power in dominant path/power in scattered path) we can see that if K=0, meaning no dominant path, the channel is Rayleigh, whereas if K>>0, the channel can be considered nonfading.

B. QPSK SYSTEM MODEL

1. Transmitted signal

A QPSK signal can be represented by

$$S(t) = S_a(t)\cos(2\pi f_c t) + S_b(t)\sin(2\pi f_c t) \tag{1}$$

where s_a and s_b are the baseband signals for the in-phase and quadrature components, respectively, and f_c is the carrier frequency. The baseband signals s_a and s_b can be expressed as a summation of data bits as

$$s_a(t) = \sum_{k=-\infty}^{\infty} a_k g_T(t-kT)$$

$$s_b(t) = \sum_{k=-\infty}^{\infty} b_k g_T(t-kT) \tag{2}$$

where g_T is the transmitter filter and T is the symbol interval. The data bits a_k and b_k can assume values {-1,1}

with equal probability and are assumed to be mutually independent.

2. Received Signal

For L cochannel interferers present, the total received signal is

$$r(t) = s_r(t) + \sum_{i=1}^{L} s_i(t) + n_{\omega}(t) \tag{3}$$

where $s_r(t)$ and $s_i(t)$ represent contributions from the desired and the ith interfering signals, respectively, and $n_{\omega}(t)$ is zero mean, additive white Gaussian noise (AWGN) with 2-sided power spectral density (PSD) of $N_0/2$ watts/Hz. Without loss of generality, it is assumed that there is no delay between the transmitted and received signal. It is also assumed that the interfering signals are QPSK modulated signals, i.e., signals generated by other ships reusing the channel. The desired signal $s_r(t)$ can be written as

$$s_r(t) = R_s s_a(t)\cos(2\pi f_c t + \theta) + R_s s_b(t)\sin(2\pi f_c t + \theta) \tag{4}$$

where R_s represents the channel amplitude gain affecting the desired signal and the phase θ includes the transmitter to receiver carrier phase differences and the random phase introduced by the fading channel. $s_i(t)$ can be written as

$$s_i(t) = R_i s_{c_i}(t)\cos(2\pi f_c t + \alpha_i) + R_i s_{d_i}(t)\sin(2\pi f_c t + \alpha_i) \quad (5)$$

where $s_{c_i}(t)$ and $s_{d_i}(t)$ represent the baseband in-phase and quadrature components of the ith interfering signal, respectively;

$$s_{ci}(t) = \sum_{k=-\infty}^{\infty} c_{k_i} g_T(t - kT - \tau_i)$$

$$s_{di}(t) = \sum_{k=-\infty}^{\infty} d_{k_i} g_T(t - kT - \tau_i) \quad (6)$$

where c_{k_i} and d_{k_i} can take values {1,-1} with equal probability and represent the in-phase and quadrature data bits of the ith interfering signal, respectively. The data bits of the interfering signals are assumed independent. τ_i is modeled as a uniformly distributed random variable(RV) ([0,T]) representing a possible offset between the symbol timing epochs of the desired and the ith interfering signals. α_i is modeled as a uniform RV ([0,2π]) representing the random phase of the ith interfering signal carrier. R_i is the fading channel gain affecting the ith interfering signal. In an AWGN environment, R_i and R_s are constants. In a frequency non-selective multipath fading environment, R_i and R_s are modeled as RV's representing the envelope of the interfering and desired signals, respectively.

3. Detection Process

At the receiver, the total received signal, r(t), is split into an in-phase component and a quadrature component and detection is then performed. Only detection of the in-phase component will be discussed. From symmetry the results for the quadrature component are similar. For optimum detection, the received signal is multiplied by locally generated quadrature carriers locked in phase with the received signal. In practice it is very difficult to achieve frequency and phase tracking in fading environments. The results presented here assume perfect frequency and phase tracking as well as symbol synchronization. Therefore, these results present an optimistic, best case scenario. The in-phase demodulated signal component is given by

$$X_a(t) = 2r(t)\cos(2\pi f_c t) \tag{7}$$

From the previous definition of $r(t)$, it can be shown that $X_a(t)$ can be written as

$$X_a(t) = R_s S_a(t)[1-\cos(4\pi f_c t)] + R_s S_b(t)\sin(4\pi f_c t)$$

$$+\sum_{i=1}^{L} R_i\{S_{c_i}(t)[\cos(\alpha_i)-\cos(4\pi f_c t+\alpha_i)] + S_{d_i}(t)[\sin(4\pi f_c t+\alpha_i)-\sin(\alpha_i)]\}$$

$$+2n_w(t)\sin(2\pi f_c t) \tag{8}$$

After low pass filtering, assuming a square root raised cosine filter [4], the signal at the output of the receiver filter $y_a(t)$ can be written as

$$y_a(t) = R_s V_a(t) + \sum_{i=1}^{L} \{R_i[V_{c_i}(t)\cos(\alpha_i) - V_{d_i}(t)\sin(\alpha_i)]\} + n(t) \qquad (9)$$

where

$$V_a(t) = \sum_{k=-\infty}^{\infty} a_k g(t-kT)$$

$$V_{c_i}(t) = \sum_{k=-\infty}^{\infty} c_{k_i} g(t-kT-\tau_i)$$

$$V_{d_i}(t) = \sum_{k=-\infty}^{\infty} d_{k_i} g(t-kT-\tau_i) \qquad (10)$$

where g(t) is the overall impulse response of the cascade of the transmitter and receiver filters and is given as [5]

$$g(t) = \frac{\sin(\pi t/T)}{(\pi t/T)} \frac{\cos(\pi\beta t/T)}{1-4\beta^2 t^2/T^2} \qquad (11)$$

where β<1 is the filter roll-off factor.

The bandwidth occupied by the signal beyond the Nyquist frequency $1/2T$ is called the excess bandwidth and is usually expressed as a percentage of the Nyquist frequency. For example, when $\beta = 0.5$, the excess bandwidth is 50%, and when $\beta = 1$, the excess bandwidth is 100% [5].

C. ERROR RATE ON AWGN CHANNEL

Without loss of generality we can assume zero delay between the transmitter and receiver, i.e., t=0. In that case

$$y_a(0) = R_s V_a(0) + \sum_{i=1}^{L} \{R_i[V_{c_i}(0)\cos(\alpha_i) - V_{d_i}(0)\sin(\alpha_i)]\} + n(0) \tag{12}$$

Substituting (10) into (12), $y_a = y_a(0)$, we obtain

$$y_a = a_0 R_s + \sum_{i=1}^{L} z_i + n(0) \tag{13a}$$

where

$$z_i = \sum_{k=-\infty}^{\infty} \{R_i[c_{k_i}\cos(\alpha_i) - d_{k_i}\sin(\alpha_i)]g(-\tau_i - kT)\} \tag{13b}$$

The average BER is computed by first calculating the conditional probability of bit error assuming τ_i, α_i to be constants. The conditional probability of error given τ_i, α_i is

$$P_{e|\{\tau_i,\alpha_i\}} = \Pr(y_a > 0 | a_0 = -1) \tag{14}$$

This can be expressed as [6]

$$P_{e|\{\tau_i,\alpha_i\}} \cong \frac{1}{2} - s\frac{2}{\pi} \sum_{\substack{n=1 \\ n\_odd}}^{\infty} \frac{e^{-n^2 w^2/2}}{n} \sin(nwR_s) \Pi_{i=1}^{L} H_{n_i} \tag{15a}$$

where H_{n_i} is given by

$$H_{n_i} = \prod_{k=-P}^{P} [\cos(nwg_{k_i}R_i\cos\alpha_i)\cos(nwg_{k_i}R_i\sin\alpha_i)] \tag{15b}$$

$$g_{k_i} = g(-\tau_i - kT), \quad w = 2\pi / T_0 \tag{15c}$$

and T_0 is a parameter that controls the accuracy of the results. The number of symbols from each cochannel interfering signal affecting a symbol decision is 2P+1 where P is chosen large enough such that the results are not changed significantly by changes in P. A typical value is P=10. From the conditional probability of error, the average BER is obtained as [4]

$$P_e \cong \frac{1}{2} - \frac{2}{\pi} \sum_{\substack{n=1 \\ n\_odd}}^{\infty} \frac{e^{-n^2 w^2/2}}{n} \sin(nwR_s)\, A_n^L \tag{16a}$$

where

$$A_n = \frac{1}{2\pi T} \int_0^{2\pi} \int_0^T \{ \prod_{-P}^{P} [\cos(nw\, g_{k_i} R_i \cos\alpha_i)]) \cos(nw\, g_{k_i} R_i \sin\alpha_i)\} \, d\tau_i \, d\alpha_i \tag{16b}$$

which can be evaluated numerically.

Equation (16) is the BER for a QPSK system with L cochannel interferers in an AWGN channel where the signals do not experience fading.

D. ERROR RATE ON FADING CHANNELS

In a fading environment the amplitudes of the desired and interfering signals, R_s and R_i, respectively, are modeled as random variables. The conditional BER is given by the AWGN channel equation (16) where the conditioning is on

R_s and R_i. The effect of fading is accounted for by averaging the conditional BER over all values of R_s and R_i. If the interfering signals experience Rayleigh fading, then R_i for the ith interfering signal is modeled by the PDF

$$f_{R_i}(r) = \frac{2r}{\Omega_i} e^{-r^2/\Omega_i}, \quad \Omega_i = E[R_i^2] \tag{17}$$

For

$$X_i = R_i \cos(\alpha_i), \quad Y_i = R_i \sin(\alpha_i) \tag{18}$$

it can be shown that X_i and Y_i are independent, zero-mean Gaussian RV's each with variance $\Omega_i/2$. The conditional probability of bit error can be written as

$$P_{e|\{R_s, X_i, Y_i\}} \cong \frac{1}{2} + \frac{2}{\pi} \sum_{\substack{n=1 \\ n\_odd}}^{\infty} \frac{e^{-n^2 w^2/2}}{n} \sin(nwR_s) \prod_{i=1}^{L} A_n^L \tag{19a}$$

where

$$A_n = \frac{1}{T} \int_0^T \{ \prod_{-P}^{P} [\cos(nwg_{k_i} X_i)]) \cos(nwg_{k_i} X_i)\} d\tau_i \tag{19b}$$

Averaging equation (19) over all values of R_s, X_i, and Y_i we obtain the average BER in fading conditions as

$$P_e \cong \frac{1}{2} - \frac{2}{\pi} \sum_{\substack{n=1 \\ n\_odd}}^{\infty} \frac{e^{-n^2 w^2/2}}{n} B_n A_n^L \tag{20a}$$

where

$$B_n = \int_0^{\infty} \sin(nwr) f_{R_s}(r) dr \tag{20b}$$

$$A_n = \frac{4}{T} \int_0^T \{ \int_0^{\infty} \prod_{-P}^{P} \cos(nw g_{k_i} x) f_{x_i}(x) dx \} d\tau_i \tag{20c}$$

$$f_{x_i}(x) = \frac{1}{\sqrt{\pi \Omega_i}} e^{-x^2/\Omega_i} \tag{20d}$$

and $f_{R_s}(r)$ is the PDF of the envelope of the desired signal.

If we assume that the desired signal experiences Ricean fading, then $f_{R_s}(r)$ is given by

$$f_{R_s}(r) = \frac{2r(1+K)}{\Omega_s} \exp\left(-K - \frac{(1+K)r^2}{\Omega_s} \right) I_0(2r\sqrt{K(1+K)/\Omega_s}) \tag{21}$$

where

$$K = \frac{\textit{power in line of sight component}}{\textit{power in random components}}, \qquad \Omega_s = E\left[R_s^2\right], \tag{22}$$

and I_0 is the modified Bessel function of the first kind and order zero. When K=0 there is no LOS component and the Ricean PDF reduces to a Rayleigh PDF. When $K \to \infty$, there is no fading. In the maritime environment being considered, the value of K will vary with sea state and atmospheric conditions. Substituting $f_{R_s}(r)$ into equation (20b), we obtain the value for B_n, which can be evaluated numerically. Equation (20a) can be used to evaluate the BER for a QPSK system with L cochannel interferers under fading conditions. The coefficients A_n and B_n are determined

numerically. Figures 3.1 and 3.2 are plots of the BER for a QPSK system with cochannel interferers in an AWGN channel [4], i.e., no fading. Figure 3.3 is a plot of the BER for a QPSK system with one cochannel interferer and a fading channel [4]. The bottom horizontal axis is labeled SNR and the top horizontal axis is labeled E_b/N_o. For a system with excess bandwidth of 50%, i.e., $bandwidth = (3/2) \times (symbol\,rate/2)$, it can be shown that E_b/N_o in dB is given by [7]

$$E_b/N_o = SNR + 10\log_{10}(bandwidth/2 \times symbol\,rate) = SNR + 10\log_{10}(3/8)$$

$$E_b/N_o = SNR - 4.26\,dB$$

From Figures 3.1 and 3.2 we can see the impact of interference on the BER. For instance, for the case L=1 and signal-to-interference ratio (SIR) = 10 dB, we obtain a BER of 10^{-6} with $E_b/N_o \approx 16$ dB. The same BER can be achieved with $E_b/N_o \approx 11$ dB when SIR is improved to 15 dB. We also note that we must pay a penalty in the SNR, alternatively E_b/N_o, needed to achieve a particular BER. For a QPSK system with no cochannel interference, $E_b/N_o \approx 10.1$ dB is required to achieve a BER of 10^{-6}. Therefore, the penalty, or additional SNR needed, due to interference is 6 dB and 1 dB for SIR of 10 and 15 dB, respectively.

In Figure 3.3 we can see the combined effect of fading and cochannel interference. Even with $E_b/N_o \approx 26$ dB, the BER is on the order of 10^{-4}. We can also see that after some threshold E_b/N_o is exceeded, increasing E_b/N_o has little impact on the BER. An increase in the desired signal level has the effect of increasing both E_b/N_o and the SIR and, therefore, should provide improved performance.

From Figure 3.1 we see that in AWGN the BER is smaller for L=1 than for L=6. That is, the performance is worst when the interference power is spread between many interferers. From Figure 3.3 we see that the reverse is true when operating in a fading channel; although, the effect is not as pronounced. Therefore, in a fading channel, one interferer is the worst case scenario.

The next chapter describes the experimental procedure and equipment setup.

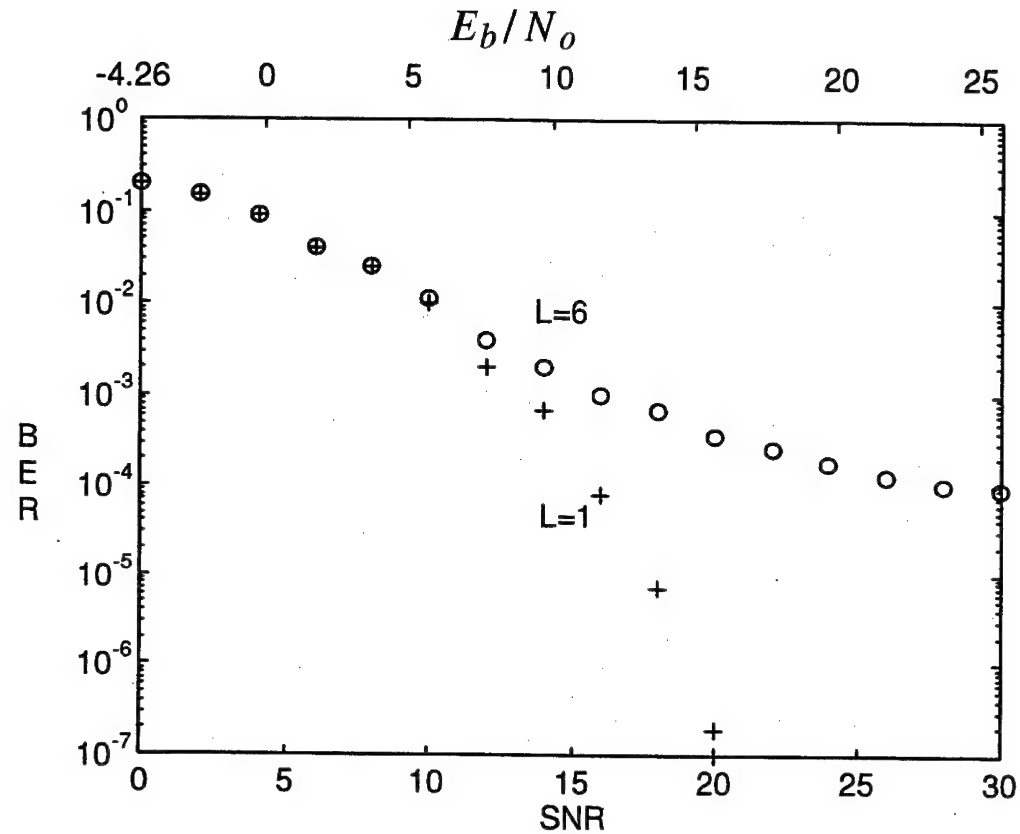

Figure 3.1 Average BER for QPSK in AWGN with L cochannel interferers and SIR = 10 dB. After Ref. [4].

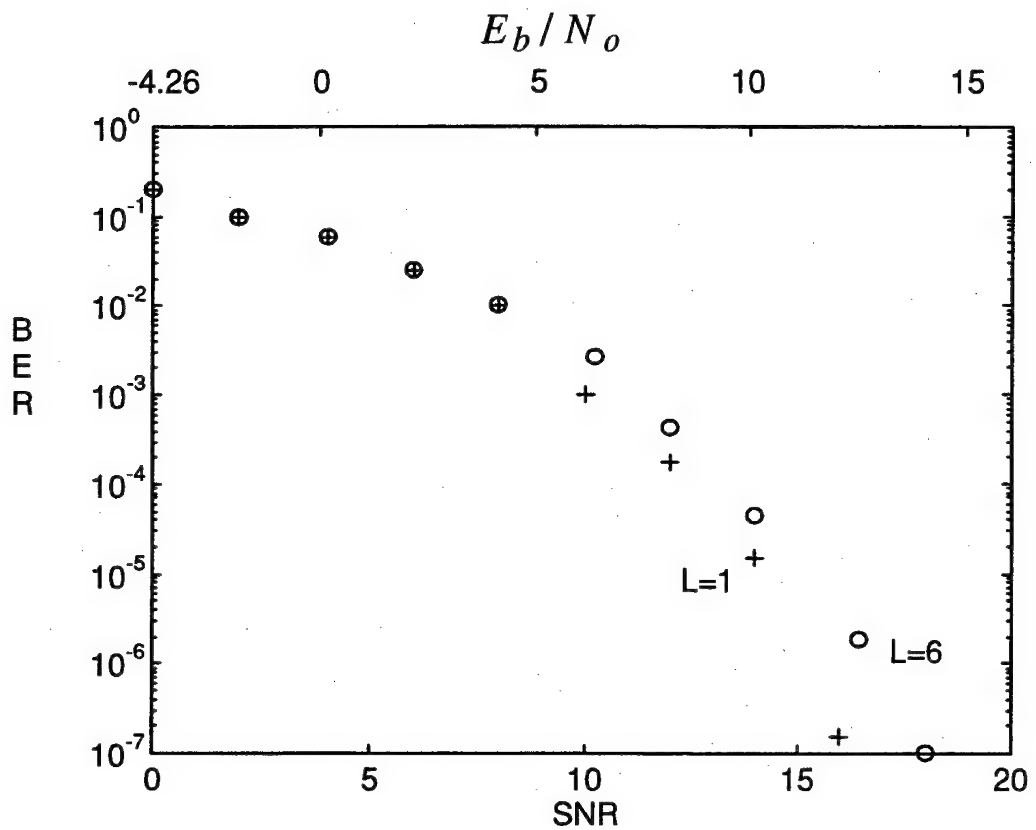

Figure 3.2 Average BER for QPSK in AWGN with L cochannel interferers and SIR = 15 dB. After Ref. [4].

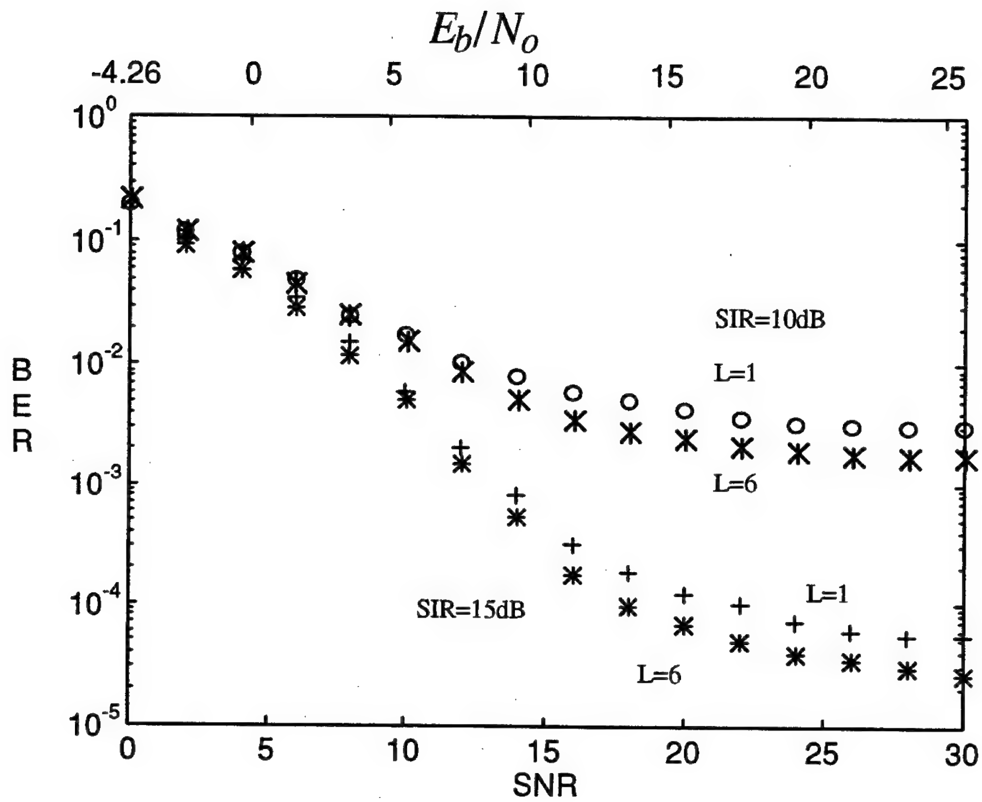

Figure 3.3 Average BER of QPSK in fading channel with L cochannel interferers and SIR = 10, 15 dB. Interferers experience Rayleigh fading, while desired signal experiences Ricean fading with K = 16. After Ref. [4].

IV. EXPERIMENTAL PROCEDURE AND EQUIPMENT SETUP

A. MENTOR GRAPHICS ENVIRONMENT

In order to study the effects of radiated power control, a telecommunications system computer simulation was developed. The simulation was developed using the Mentor Graphics® (MG) computer software communications library, hereafter referred to as the telecom library. The Mentor Graphics software runs on a SUN computer workstation and makes use of ICUCOM corporation's ACOLADE® software. The telecom library allows users to implement a Monte Carlo simulation for a communication system of arbitrary complexity. The telecom library contains modules commonly encountered in telecommunication systems. A telecommunication system simulation is implemented by performing the following basic steps:

1. A system block diagram of arbitrary complexity is developed using MG Design Architect (DA) tool. The DA provides a graphical user interface which allows users to choose blocks to be added to the communications model. See Figure 4.1 for a telecommunication system simplified block diagram.
2. Once the model is constructed, the user can modify a number of parameters within each block. For

example, the energy of the transmitted signal, the power spectral density, etc.

3. The user then performs a "check" of the diagram by using the check command, which warns the user of improper connections within the diagram.
4. The user executes the "Create Design Viewpoint" command. The design viewpoint creates an executable version of the simulation. Once the design viewpoint is created the user can exit the design architect tool and proceed to the simulation execution tool, DDSim.
5. The Monte Carlo simulation is executed from the DDSim tool. DDSim allows the user to modify all the parameters, such as signal power and noise power spectral density, that were modifiable in the design architect environment. In addition DDSim can produce eye diagrams, bit error rate plots, histograms, time diagrams, etc. These tools are extremely useful when characterizing a system. Bit error rate data can be saved to a text file which can be read by MATLAB® software.

For this thesis a quadrature phase shift keying (QPSK) system simulation was implemented. Various conditions of cochannel interference and radiated power control have been modeled. Figure 4.1 presents a simplified block diagram of

a data communication system. To follow is a basic description of each block and how each block is implemented by Mentor Graphics/ACOLADE software.

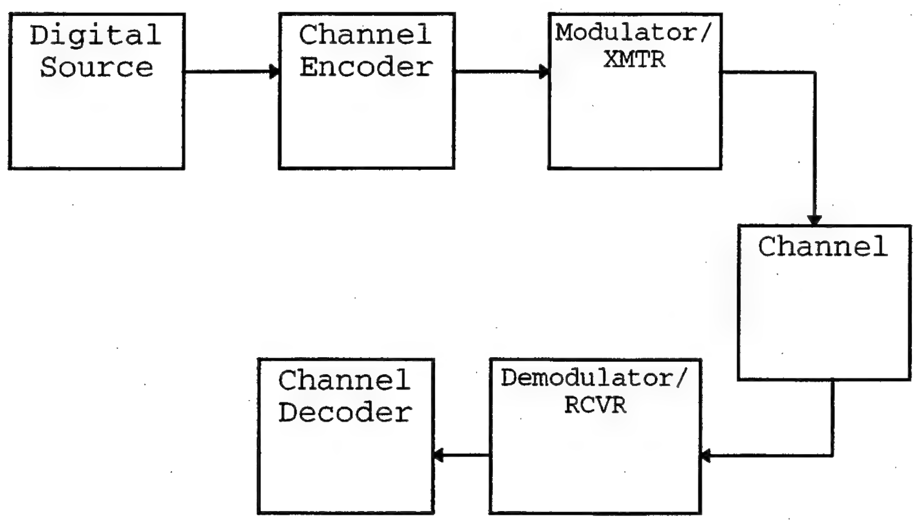

Figure 4.1 Block diagram of basic data communication system

a. Digital Source - The digital source produces a sequence of discrete symbols drawn from a given alphabet. This sequence is to be transmitted over a specified channel, reconstructed, and delivered to a remote destination. The single most important measure of system performance is the probability that the receiver's estimate of the transmitted sequence is different from the actual transmitted sequence. In the simulation the probability of

error is determined through statistical analysis using Monte Carlo simulation techniques. In terms of Figure 4.1, the simulation environment begins by generating a pseudo-random symbol sequence emitted by the data source. The length of the sequence can be selected by the operator. The sequence is then passed to each module in the system topology where a software model of each block is invoked to apply the appropriate data transformation. The level of detail and accuracy of the simulation model is a trade-off against simulation time and is a fundamental part of the entire modeling and simulation process.

b. Channel Encoder- The channel encoder can be used to add controlled redundancy to the symbol sequence to be transmitted in order to protect data. It maps the sequence of discrete symbols produced by the digital source into a new sequence of symbols drawn from a different alphabet. The purpose of this is to introduce controlled redundancy, which can be used on the receive side to reconstruct the transmitted sequence more faithfully. In other words, using a suitable coding strategy the error probability can be improved for a given SNR of the received signal. Two fundamental types of coding exist and are supported by the telecom library:

1)Block Coding

2)Convolutional Coding

c. Modulator/Transmitter- The modulator/transmitter maps the digital sequence into an analog form suitable for transmission over the channel. For each value of the input sequence which is presented to the transmitter every T_C seconds, the transmitter produces a predefined signal. The predefined signal is a function of the modulation technique being employed. The telecom library supports M-ary Frequency Shift Keying (MFSK), M-ary Phase Shift Keying (MPSK), Quadrature Amplitude Modulation (QAM), and differential MPSK.

d. Channel- The transmission channel provides the connection between the information source and destination. In the simulation, all sources of degradation that are beyond control are incorporated into the channel model. The waveform generated by the modulator/transmitter is modified according to some physical model implemented by the channel block. The telecom library supports a variety of channel models, including multipath fading, and additive white Gaussian noise (AWGN), which can be used alone or in combinations.

e. Demodulator/Receiver- The main function of the demodulator/receiver is to perform data demodulation of the channel output in order to derive an estimate of the original transmitted sequence. In addition to the basic demodulation functions, the receiver must perform a variety of ancillary functions, such as phase and frequency tracking, bit synchronization, automatic gain control (AGC) and others. Receivers in the telecom library are constructed hierarchically and contain subsystems to perform these additional functions.

f. Channel Decoder- The channel decoder uses the controlled redundancy added by the channel encoder to correct a number of errors induced by the transmission channel and, therefore, reduce the error probability.

B. SIMULATION MODEL DESCRIPTION

The system modeled is shown in Figure 4.2. This is a QPSK system containing the basic elements discussed in the previous section, plus an additional interference source and an error counter.

1. Interference Source

The interference source is modeled as another QPSK system operating in the same frequency band and at the same

data rate. This model is used because we are interested in interference generated by other ships re-using the channel.

2. Data Sources

The data sources produce two independent binary random data sequences. This is accomplished by using a different seed for each data source.

3. Fading Channel Model

Both the interfering and desired signal experience fading, and the fading channels are each modeled as 3-path fading channels. It consists of direct, diffuse (multipath), and specular (reflected) paths. The user specifies the percentage of each component on the total signal strength, as well as the phase of the specular component. In a maritime environment the contribution of the specular component, both magnitude and phase, will vary randomly. However, this effect cannot be modeled in the telecom library. Therefore, the contribution of the specular component was set to zero and its effect included in the diffuse component. When only the diffuse component is present, the channel is modeled as Rayleigh. When diffuse and direct components are present, the channel is modeled as Ricean with the parameter K=(power in dominant path/power in diffuse path).

It is assumed that the transmitters are employing a power control scheme that will automatically increase transmitted power to partially compensate for fading

conditions and interference. When this is the case, the depth of fading experienced by the desired signal will be significantly less than that experienced by the interfering signal. This effect is modeled by describing the interfering channel model as a Rayleigh fading channel.

In order to model an interferer using a power control scheme, the interferer's output is weighted by a Rayleigh distributed random number with mean of 1.0. The reason for this is that an independent observer "looking" through an independent Rayleigh channel will observe an interfering source varying its mean output with a Rayleigh distribution. Since the telecom library only provides uniform random weights, I created an array of 10,010 Rayleigh distributed random numbers using MATLAB's RAYLRND function. The uniform random source chooses one of this values for every data bit generated, providing the desired distribution.

4. Error Counter

The error counter in Figure 4.1 compares the received data with a replica of the transmitted data. It then counts the number of bit errors in the received data sequence and outputs this data to a user definable text file which is then saved as a MATLAB's m-file.

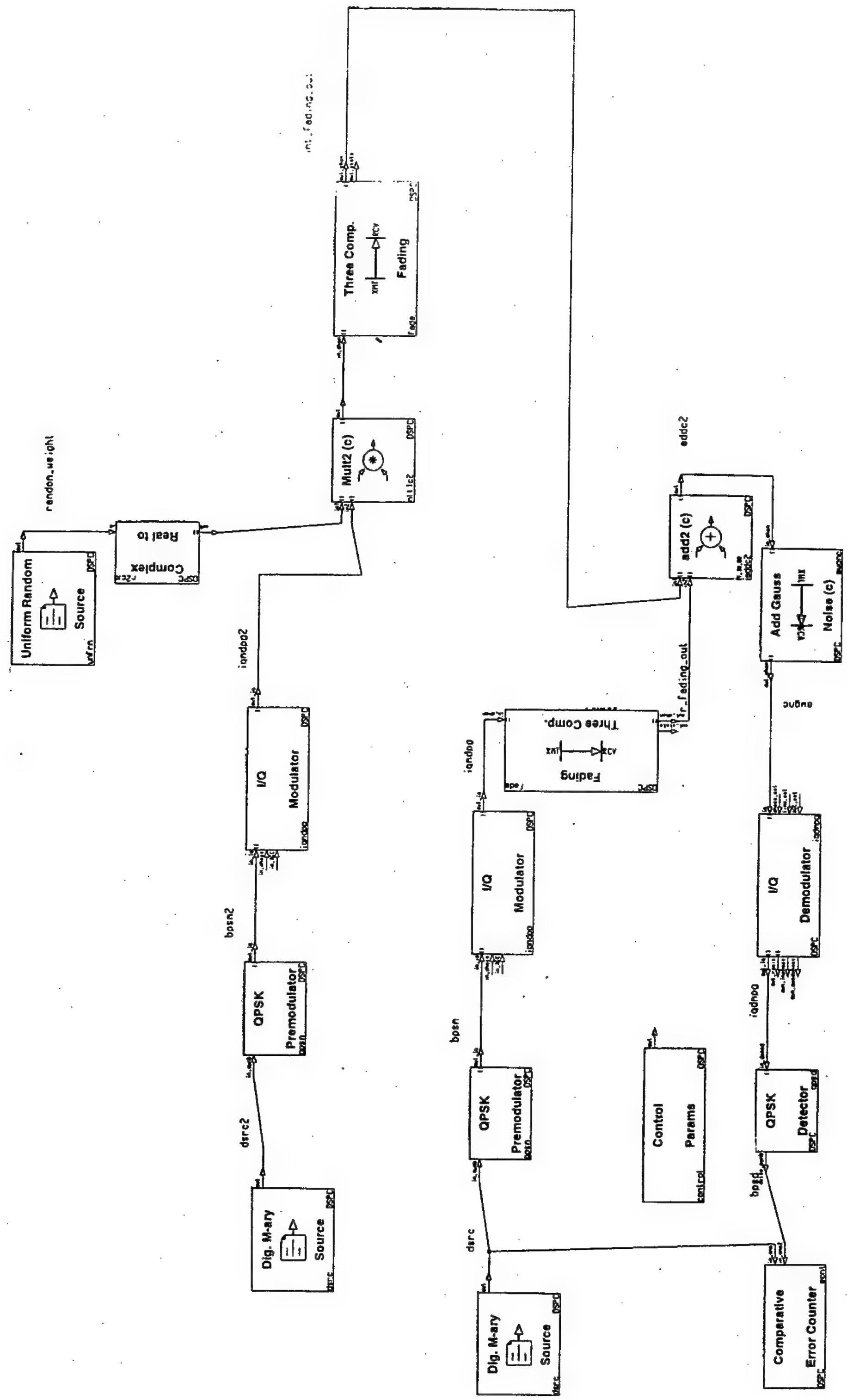

Figure 4.2 QPSK System Model

C. TEST CASES

Table 4.1 lists the test cases implemented. The signal-to-interference ratio (SIR) is maintained constant throughout each test case while E_b/N_o is increased until either a bit error rate of approximately 10^{-6} is obtained or E_b/N_o = 30 dB is reached. The number of errors required to generate a data point is a user definable quantity. This is a very important parameter and is a trade-off between simulation accuracy and speed. The minimum number of errors is set to 25 for all test cases. For each data point desired, the simulation will run until 25 errors are obtained. It then writes the BER value to the user-specified text file. A 10^{-6} BER implies that approximately 25 million data bits must be generated for that data point. This proved to be a very time consuming process, requiring up to 10 hours of computing time to generate each plot. Additionally, the Mentor Graphics software cannot be run in background mode, which limits the user to running processes in one dedicated machine.

Since the theoretical bit error rate for QPSK in AWGN is a well known relationship, it is used as a baseline to test simulation accuracy. The accuracy of the results obtained for the QPSK system in AWGN can then be used as a measure of confidence on other simulation results.

1. QPSK in Additive White Gaussian Noise(AWGN)
2. QPSK in Ricean Fading for K = 2,5,10,20
3. QPSK in Ricean Fading (K=20) with One Interferer. Interfering Signal Experiences Rayleigh Fading. SIR = 10, 20, 30 dB
4. QPSK in Ricean Fading (K=5) with One Interferer. Interfering Signal Experiences Rayleigh Fading. SIR = 10, 20 dB
5. QPSK in Ricean Fading (K=20) with One Interferer. Interfering Signal Experiences Rayleigh Fading. SIR = 10, 20, 30 dB. Desired signal employs power control.
6. QPSK in Ricean Fading (K=5) with One Interferer. Interfering Signal Experiences Rayleigh Fading. SIR = 10, 20 dB. Desired signal employs power control.

Table 4.1 Monte Carlo Simulation Test Cases

V. RESULTS

Figures 5.1 through 5.8 show simulation results for test cases listed in table 4.1. The goal of these simulations is to obtain the BER for QPSK under various conditions of fading and cochannel interference.

A. QPSK IN AWGN

Figure 5.1 shows the effect of averaging 10 and 25 errors for QPSK in AWGN. For every data point the simulation executes until the minimum number of errors is reached. It then writes the current BER to a file and then proceeds to the next point. The results are close to the theoretical values, but we observe a larger deviation when only 10 errors are averaged. Based on these results, it was decided to average a minimum of 25 errors per data point. The penalty paid for averaging 25 errors is a longer running time.

B. QPSK IN RICEAN FADING AND NO INTERFERENCE

Figure 5.2 shows the effect of a Ricean channel with K = 2, 5, 10, 20. We can notice a significant degradation in the BER for K = 2,5,10. For K=10, assuming a constant slope in Figure 5.2, we need $E_b/N_o \approx 40$ dB to obtain a BER

of 10^{-6}. When K = 20, $E_b/N_o \approx 15$ dB is required to provide a BER of 10^{-6}.

If a single, omnidirectional antenna is to be used, we see that a very large fading margin will be required for K = 2, 5, 10, while for K=20 the fading margin will be on the order of 5 dB. For the shipboard LOS system being considered, it was shown in Chapter 2 that the maximum communication range attainable (BER = 10^{-6}) with AWGN is approximately 22 km. If an additional 5 dB margin is to be allocated, the maximum range is reduced to 18 km. For the case K = 10, the maximum range is reduced to 5 km.

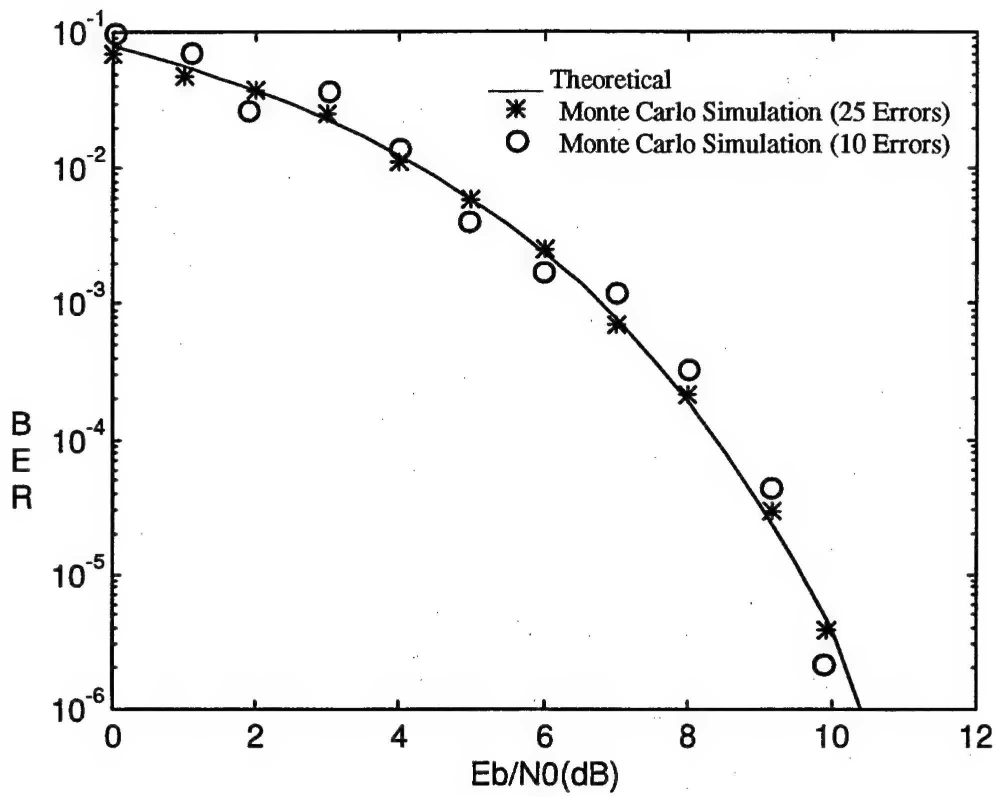

Figure 5.1 Theoretical bit error rate for QPSK in AWGN and simulation results for minimum of 10 and 25 errors.

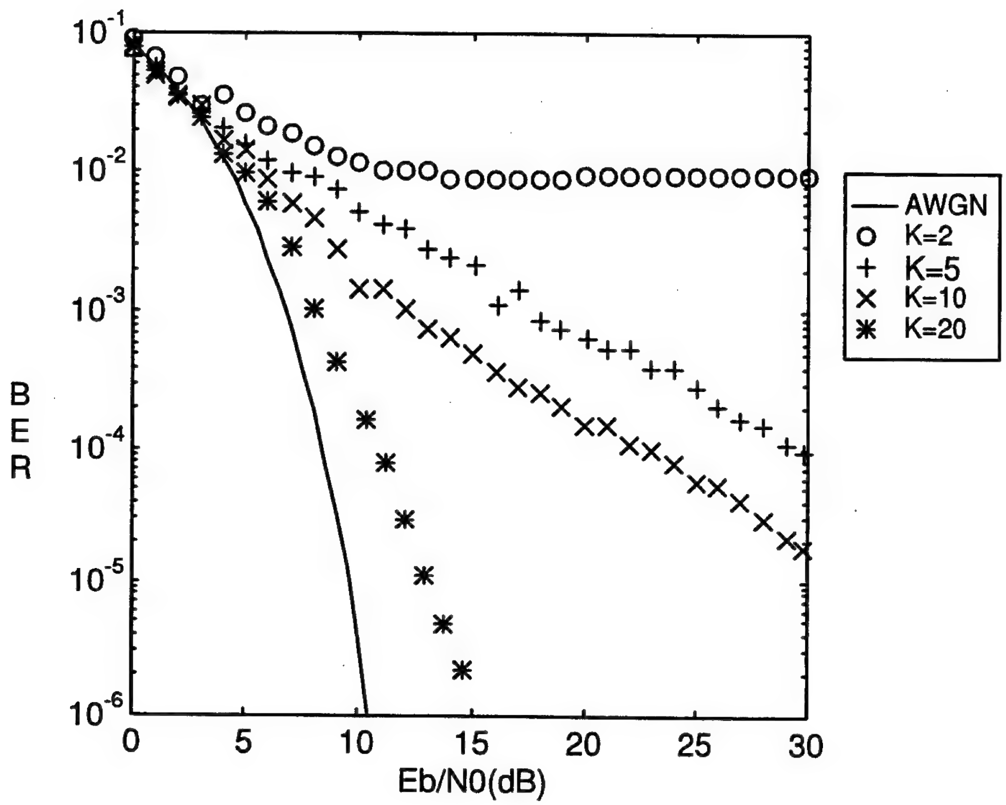

Figure 5.2 Bit error rate for QPSK in Ricean fading for K=2,5,10,20.

C. QPSK IN RICEAN FADING WITH COCHANNEL INTERFERENCE, K=20

Figure 5.3 is a plot of simulation results for QPSK in Ricean fading channel, K = 20, with cochannel interference and SIR of 10,20,30 dB. It is assumed that the interfering signal suffers Rayleigh fading. We can see that when SIR = 30 dB, $E_b/N_o \approx 18$ dB is required to obtain a BER of 10^{-6}. Recalling that -80 dBm were required to obtain $E_b/N_o = 10.6$ dB, we see that -72 dBm are required to obtain $E_b/N_o = 18$ dB. An SIR of 30 dB implies an interfering signal with approximately -102 dBm mean. The minimum range between the interferer and the desired signal receiver will be a function of the interferer's output power. For example, if interferer's output power is 10 dBm, the signal must suffer a 112 dB loss. From Figure 2.4, this corresponds to approximately 20 km. Table 5.1 lists similar results for interferer with output power of 10, 20, 30 and 40 dBm. Reuse range is that range at which the interferer can reuse the frequency channel and still maintain an acceptable level of interference, where acceptable is defined as SIR of 30 dB or higher.

Interferer Output Pwr **dBm**	**Path Loss Required for SIR = 30 dB** **dB**	**Reuse Range** **km**
10	112	15
20	122	25
30	132	35
40	142	45

Table 5.1 Reusable Ranges for QPSK Modulation in Ricean Fading with K=20 and SIR = 30 dB.

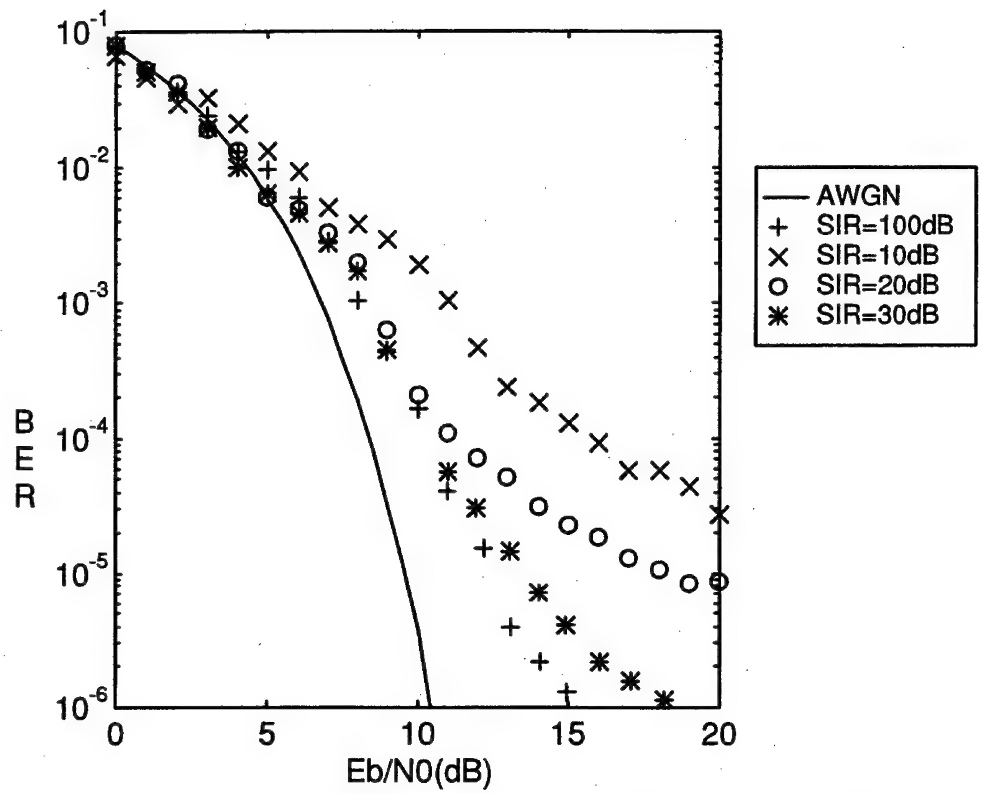

Figure 5.3 Simulation results for QPSK with cochannel interference in Ricean fading channel with K=20. No power control is used by interferer.

Figure 1.1, renumbered as 5.4 for convenience, is an illustration of a group of 4 ships reusing a full duplex channel. It is assumed that ship A transmits in channel 1 and receives in channel 2. Ship B transmits in channel 2 and receives in channel 1. Suppose that the desired signal is the signal being received by ship B (channel 1), and the interfering signal is generated by ship D. Now consider the cases when the interferer's (ship D) output power is 10, 20, 30 and 40 dBm respectively. A 10 dBm output power from ship D requires ship C to be within a range of 2 km in order to maintain $E_b/N_o \approx 18$ dB at ship C. This interferer-to-intended-receiver range(r) increases to 5, 8, and 15 km when ship D increases its output power to 20, 30 and 40 dBm, respectively. Figure 5.5 illustrates the relationship between reuse range (R), and the maximum separation between the interferer (ship D) and its intended receiver (ship C).

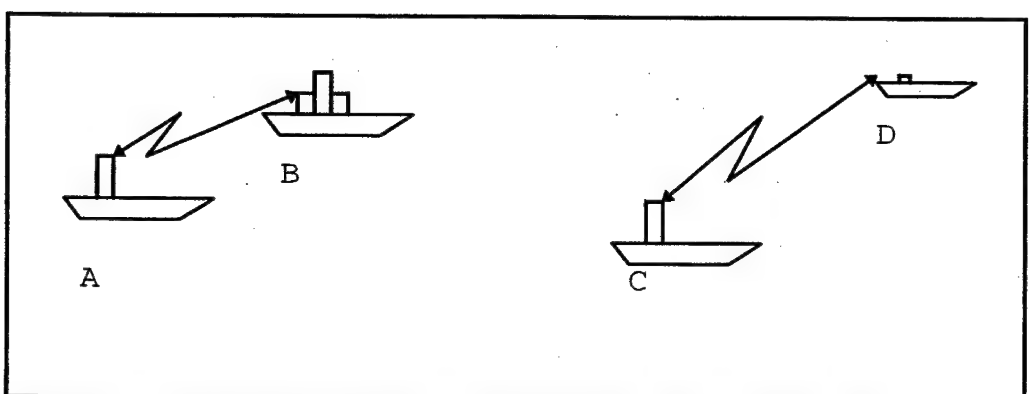

Figure 5.4 RF wireless communications network within a BG or ARG

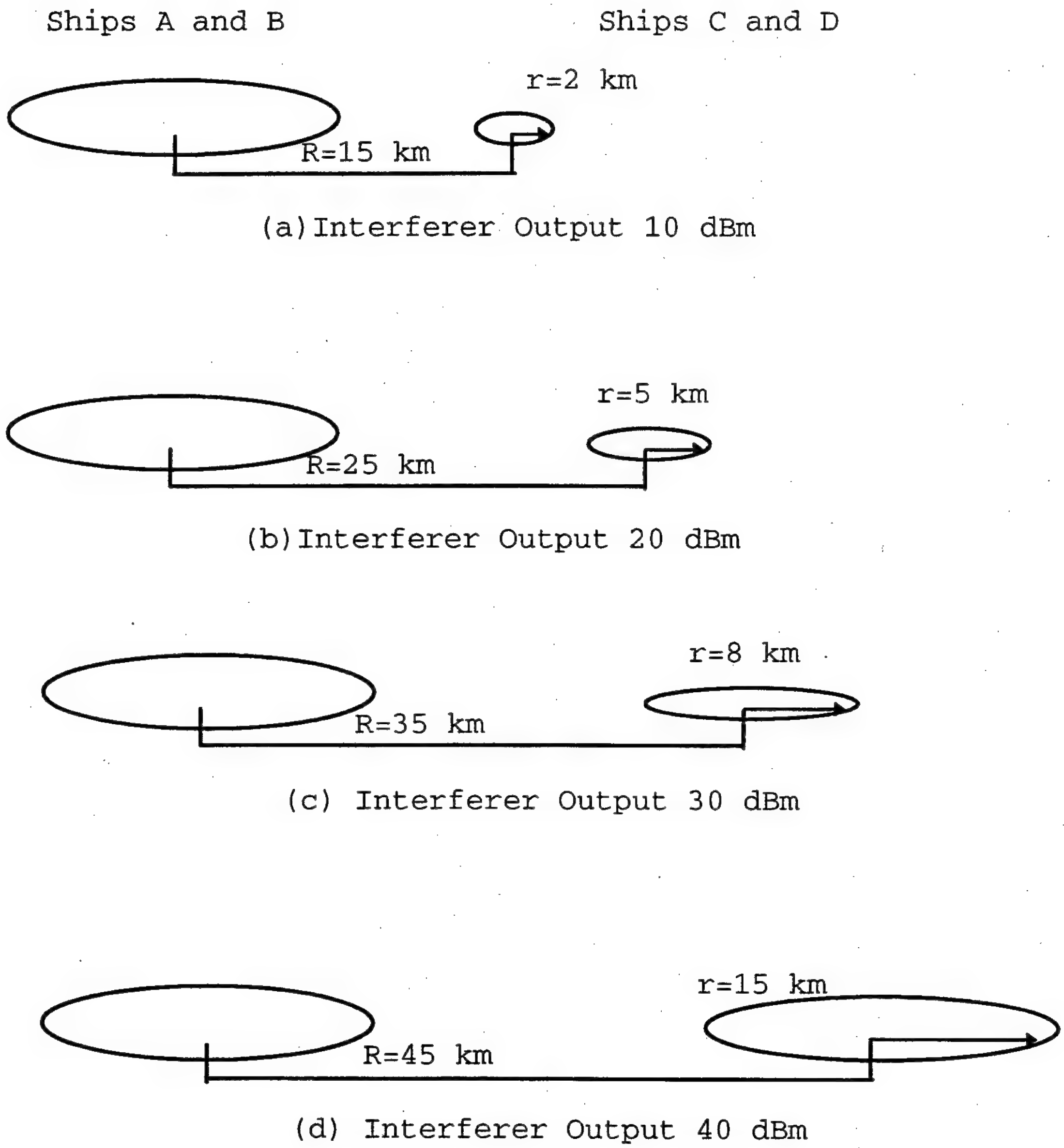

Figure 5.5 Reuse range (R) vs interferer output power and interferer-to-intended receiver range (r)

D. QPSK IN RICEAN FADING WITH COCHANNEL INTERFERENCE, K=5

Figure 5.6 is a plot of simulation results for Ricean channel with K = 5. Even when SIR = 100 dB the BER is approximately 10^{-4}. If the SIR = 100 dB curve has a constant slope, then $E_b/N_o \approx 50$ dB is required to obtain a BER of 10^{-6}. This corresponds to a received signal of -40 dBm. In order to maintain $E_b/N_o = 50$ dB, a +40 dBm output signal can sustain an 80 dB loss. This corresponds to a range of less than 2 km. In other words, with the transmitter output at its maximum, the communications range will not exceed 2 km.

E. QPSK IN RICEAN FADING AND INTERFERER USES POWER CONTROL

Figures 5.7 and 5.8 are plots of simulation results when interferer employs a power control scheme to compensate for signal fades between the interferer and its intended receiver. The effect of employing power control to compensate for path losses can be deduced from the previous section and is not considered here. The results are very similar to the results obtained for an interferer not employing power control. However, an interferer employing power control is able to operate with a lower mean output power. For example, referring to Figure 5.4, when no power control is used ship D must operate with a mean output power of 40 dBm. If the power control algorithm is capable of

tracking signal fades, ship D may be able to operate with a mean power output of 30 dBm. This implies that the reuse range will decrease from 45 to 35 km. The amount of power by which the mean is reduced will depend on the effectiveness of the system tracking signal fades.

F. THEORETICAL VS. SIMULATION RESULTS

A comparison between Figures 3.3 and 5.3 shows that simulation results are close to theoretical results for small E_b/N_o values. However, for large E_b/N_o the results diverge and the simulation predicts a BER lower than theoretical. For instance, when SIR = 10 dB both models predict BER = 10^{-2} for $E_b/N_o \approx 7$ dB. However, for $E_b/N_o = 15$ dB, the simulation predicts BER $\approx 10^{-4}$ while the theory predicts BER $\approx 4\times10^{-3}$.

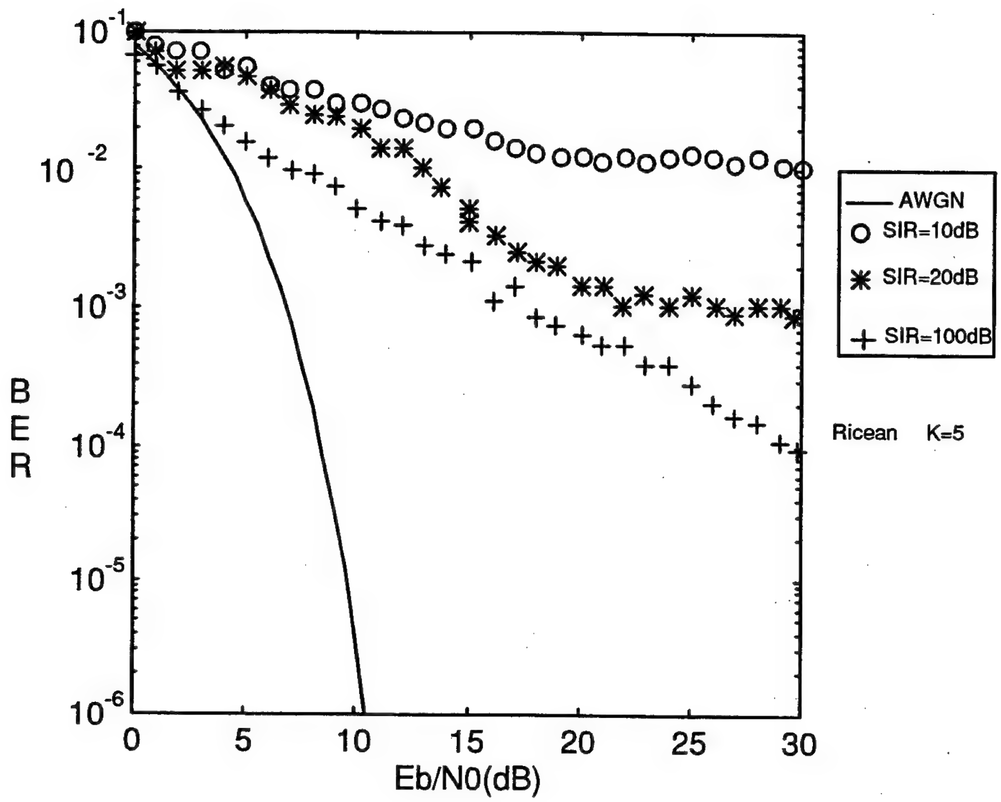

Figure 5.6 Simulation results for QPSK with cochannel interference in a Ricean fading channel with K = 5. No power control is used by interferer.

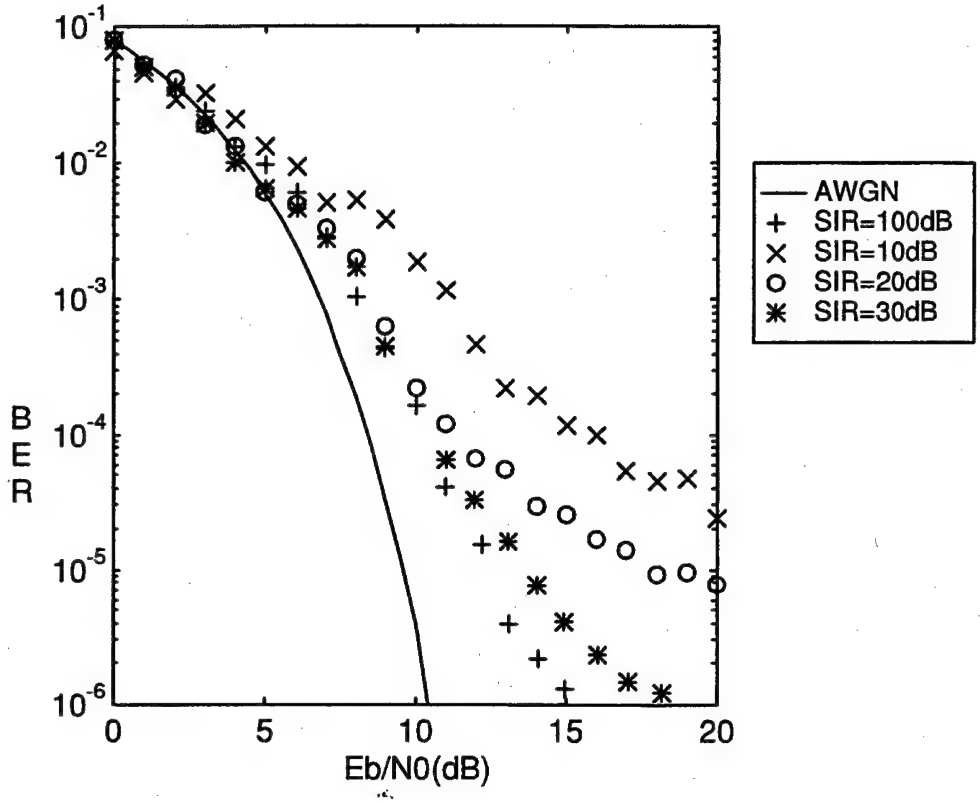

Figure 5.7 Simulation results for QPSK with cochannel interference in a Ricean fading channel with K = 20. Interferer uses power control.

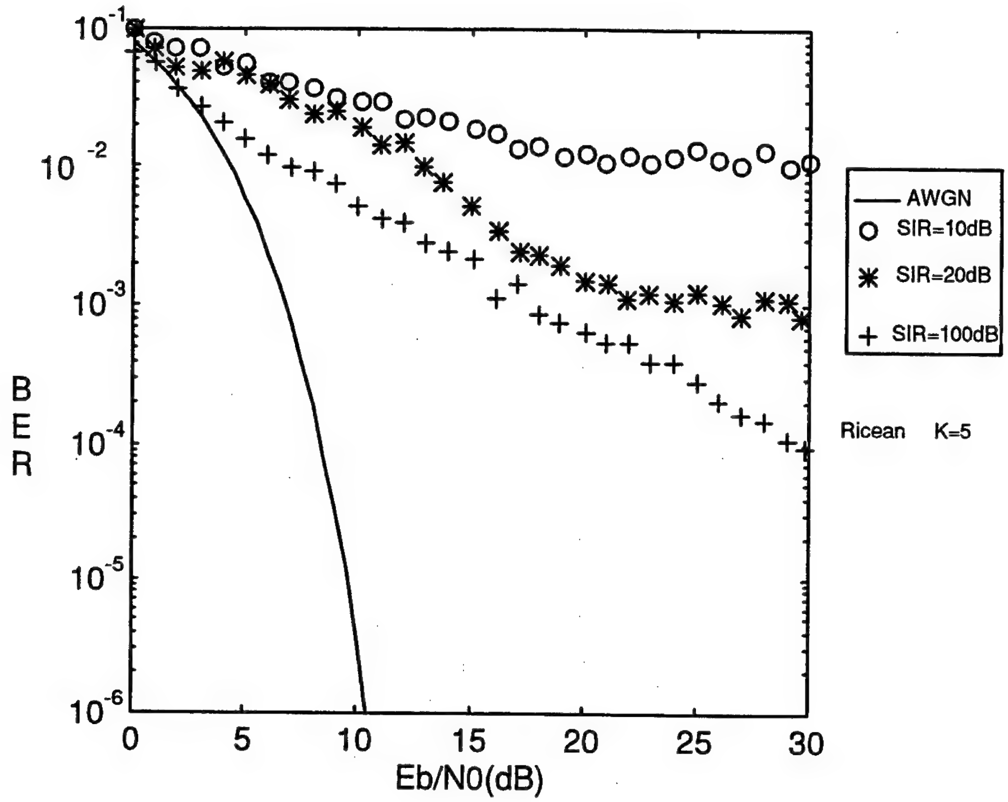

Figure 5.8 Simulation results for QPSK with cochannel interference in Ricean fading channel with K = 5. Interferer uses power control.

VI. CONCLUSION

The performance of a QPSK communications system in fading conditions and cochannel interference was studied. Theoretical results were presented and system behavior was modeled using Monte Carlo simulation methods. Simulation results were used to determine the minimum range at which another user can operate in the same frequency channel while maintaining a signal-to-interference ratio of 30 dB. Reusable ranges were computed assuming a U.S. Navy WSC-3 UHF LOS transmitter with an output power of 10 dB watts, an antenna height of 25 meters, and a data rate of 1.5 Mbps. The WSC-3 can transmit up to 20 dB watts, but it is assumed that 10 dB are lost due to cable and antenna coupling losses in both the transmitter and the receiver.

The results obtained show that by managing the transmitted power, ships at sea can reuse a communication channel at shorter distances than when no power control is in place. This reuse range is affected by many factors but primarily by the distance between the interferer and its intended receiver. This effect is depicted in Figure 5.5, where it can be seen that when the interferer communicates with a ship within a 2 km range it can reduce its output power to 10 dBm and the reuse range can be as small as 15 km. Without the use of power control the interferer's

output power would be 40 dBm and the reuse range increases to approximately 45 km.

The ranges at which a frequency channel can be reused were computed from Mentor Graphics simulation results for one cochannel interferer, i.e., L=1. Theoretical results show that when the interfering signal experiences Rayleigh fading, L=1 is the worst case scenario and system performance will not be degraded for L greater than one. However, the assumption of a Ricean fading channel for the desired signal with K = 20 may be optimistic. This parameter will have a significant impact on communication and reuse ranges.

Although simulation results show the benefits and advantages of using power control to achieve frequency reuse; power control does not appear to be practical for the shipboard LOS high-data-rate system being considered by NRaD. This is primarily due the limited power output of the WSC-3 radios. An effective power output of approximately 10 dB watts limits communication ranges at the T1 rate to less than 20 kilometers. The addition of power control can only reduce this range and this may not be acceptable in an operational scenario.

Even without the use of power control, the channel can be reused by increasing the separation between ships reusing the channel to ranges that will guarantee an SIR of approximately 30 dB. For the radios being considered, this corresponds to a separation between ships reusing the channel of at least 45 kilometers.

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